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Microexplosion and ignition of droplets of fuel oil/bio-oil (derived from lauan wood) blends

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HIGHLIGHTS

- We explored microexplosion and ignition behaviors of bio-oil/fuel oil-blends droplets.
- Bio-oil was produced from fast pyrolysis process of wood (lauan).
- Mixing ratios of blended fuels and ambient temperatures are important parameters.
- At 500 °C, microexplosion and ignition occurred for all bio-oil/diesel blends.
- Ignition did not occur for the bio-oil contents below 50% in the bio-oil/HFO blends.

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ABSTRACT

Vaporization, microexplosion and ignition characteristics of a single droplet of pyrolysis bio-oil/fuel oil blends were examined using a suspended-droplet heating device. The bio-oil used in the experiment was produced from the fast pyrolysis process of lauan (*shorea*) wood, which is of low heating value, and high water as well as oxygen contents. The heating temperature (ambient temperature) and the mixing ratio of bio-oil/fuel oil blends were varied in the experiment. Two kinds of fuel oil were adopted, i.e., diesel and heavy fuel oil (HFO). The droplet evaporation, microexplosion and ignition behaviors were recorded by a high-speed video system. Meanwhile, the temperature histories (droplet and ambient temperatures) were measured by two K-type thermocouples in the heating process. For pure bio-oil, it was found that at the lower ambient temperature, 300 °C, random behavior (including expansion, bubbling, ejecting, and swelling) and microexplosion could be observed but ignition did not occur. However, at the higher ambient temperature, 500 °C, random behavior, microexplosion and ignition occurred for pure bio-oil and also for all cases of bio-oil/diesel blends. Random behavior and microexplosion occurred because the bio-oil contained many chemical compositions with various boiling points and water. For the bio-oil/HFO blends, ignition did not occur for low bio-oil contents (smaller than 50%) in the blends. However, when the bio-oil content was equal to or greater than 60%, ignition could occur but bio-oil/HFO-blends droplets took longer to finish burning compared with the bio-oil/diesel droplets.

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1. Introduction

Currently, fossil fuels are still the main options as energy source in the world. However, their availability is becoming less for each passing year. Research shows that within 40–50 years, fossil fuels will become scarce and hard to find. And not only that, fossil fuels have been proven responsible for the environmental adversities, such as global warming, acid rain, and urban smog, due to the level of pollutant emissions produced [1]. Therefore, it is necessary to find environment-friendly alternative fuels that can be produced steadily.

Biodiesels have emerged as the alternative fuels to replace fossil fuels. There are several reasons why biodiesels become good alternative fuels, which include lower emissions of greenhouse gases and pollutants (such as sulfur (virtually none), polycyclic aromatic hydrocarbon (PAH), nitrited PAH (regarded as carcinogens) and soot), reduction of deforestation, increased lubricity for long-life utilization, and a higher flash point for safer storage and management [2]. The current study focuses on bio-oils which can be produced from various types of plants such as rapeseed [3,4], sun

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flower [4], cassava [5], and sugarcane [6]. In addition, they can be produced from wood [7,8], and fish oil [9].

Pyrolysis converts energy from biomass into bio-oils by thermochemical conversion technology [10]. It involves the heating of organic materials in the absence of reagents, especially oxygen, to achieve decomposition. Pyrolysis bio-oil is black-brownish liquids obtained by the condensation of vapors during the pyrolysis of wood and other vegetable biomasses. The efficiency of the production process is very high, typically we can generate around 60–75% of pyrolysis bio-oil in weight from the raw material [11].

Pyrolysis bio-oils are multi-component mixtures of different chemical compounds derived from depolymerization and fragmentation of cellulose, hemicellulose and lignin. Therefore, the elemental composition of pyrolysis bio-oil and petroleum derived fuel is different [12,13]. Consequently, the chemical and physical properties of fast pyrolysis bio-oils affect their combustion characteristics and their storage and handling. Bio-oils are characterized by high viscosity, acidity and electrical conductivity, presence of water and various oxygenated compounds, ash and other solid impurities [14]. Bio-oils have low heating value, and do not ignite readily. Bio-oil is shown to be unstable when subjected to relatively high temperature for long periods. Another characteristic of this unstable oil is its self-polymerization [15].

Many researches were conducted about pollutant emissions and performances of power plants (or engines) using bio-oils (or ethanol) as fuel [1,16,17]. On the other hand, only a few fundamental studies put emphasis on the vaporization and combustion characteristics of bio-oil droplets. Such studies could provide the necessary basic data to characterize the mechanisms responsible for deposit formation during bio-oils combustion. Wornat et al. [18] have performed single droplet experiments with two biomass oils, produced from the pyrolysis of oak and pine. Liquid-phase polymerization and pyrolysis of the oxygenate-rich biomass oils lead to the formation of carbonaceous cenospheres. The droplet combustion characteristics of biodiesel from waste vegetable oils were investigated by Li et al. [19]. Their results show that the biodiesel droplet has higher burning rate, and that biodiesel in general has a lower propensity to generate soot because its molecular oxygen content promotes the oxidation of the soot precursors. Calabria et al. [20] investigated the combustion of pyrolysis-oil-based fuels. The microexplosion mechanism inside the droplets was found to be more important with bio-oil than with diesel fuel. According to the chemical composition of bio-oils and their esters, the residue formation is more or less important [4].

It is recognized that in practical applications the combustion of a fuel spray is significantly controlled by the combustion of each of the droplets, which constitutes the spray. Hence, the understanding of droplet behaviors including vaporization, microexplosion, ignition, and combustion is of great significance. In other words, a reliable description and useful information of spray combustion using bio-oil/fuel oil blends is extremely important which requires a comprehensive understanding of liquid fuel properties and droplet behaviors. Yet, only few fundamental studies put particular emphasis on the vaporization and combustion characteristics of bio-oil droplets. Apparently, there are gaps to be filled on understanding the mechanisms and behaviors of droplets of diesel/bio-oil blends or heavy fuel oil (HFO)/bio-oil blends. Therefore, this study aimed at advancing the understanding of the characteristics related to vaporization, microexplosion, ignition and combustion of droplets of pyrolysis bio-oil/fuel oil blends using a suspended-droplet heating device.

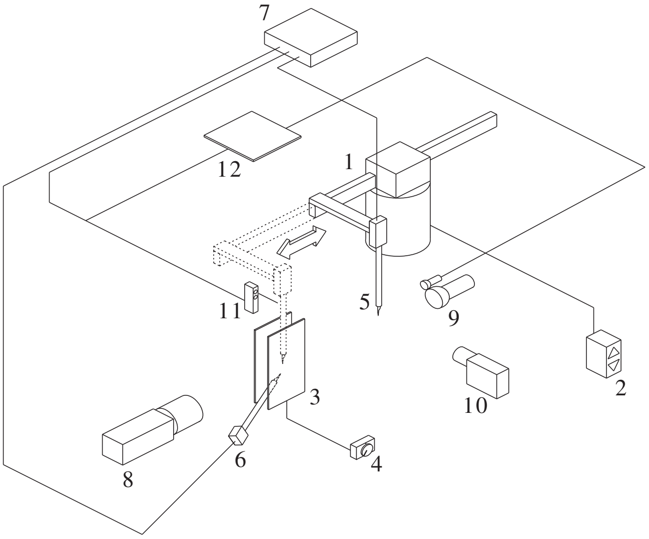
In this study, experimental results concerning the behaviors of droplet vaporization, microexplosion, and ignition of diesel/bio-oil blends or heavy fuel oil (HFO)/bio-oil blends are presented. Mixing ratios of blended fuels and temperatures of the hot environment are two important parameters investigated herein. The results are also compared with those using pure diesel, pure HFO, or pure bio-oil at the same ambient temperature.

2. Experimental setup

A schematic of the experimental apparatus is shown in Fig. 1. Two electrically heated plates (No. 3 in Fig. 1), which are of the same size, 60 mm in length and 30 mm in width, were aligned vertically 5 mm apart (shown in Fig. 2). Two K-type thermocouples of 0.07 mm diameter (shown by Nos. 5 and 6 in Fig. 1) were employed in the experiment. No. 5 is denoted by thermocouple A; No. 6 is designated by thermocouple B. Thermocouple A was positioned on the linear motion mechanism (No. 1 in Fig. 1) and could be guided to move in and out of the electrically heated plates using the motor controller (No. 2 in Fig. 1). Note that thermocouple A was used to suspend an emulsion drop of bio-oil/fuel oil blends on the tip and to measure the interior temperature of the drop. On the other hand, thermocouple B was utilized to measure the ambient temperature, which was maintained at a fixed value by the electrically heated plates with a temperature controller (No. 4 in Fig. 1). Fig. 2 shows the relative positions of thermocouples A and B in between the two heated plates when the emulsion drop was heated.

In the present study, the temperature of the hot environment was kept at a stable value (i.e., 300 °C or 500 °C) by the temperature controller during the experiment. To prepare an emulsion droplet of bio-oil/fuel oil, a tiny droplet issued from a hypodermic needle was first attached and afterwards suspended on the tip of thermocouple A outside the high-temperature environment. Then one camera shooting (No. 10 in Fig. 1) was conducted after the droplet was hung on thermocouple A to determine the initial droplet size before the heating experiment began.

The experiment began with the movement of thermocouple A to the heated plates by turning on the motor. When an expected



1. Linear motion mechanism	7. Data acquisition system
2. Motor controller	8. High speed camera
3. Electrically heated plate	9. LED lamp (the light)
4. Temperature controller	10. Digital camera
5. Thermocouple A (moved)	11. Switch (trigger) of the light
6. Thermocouple B (fixed)	12. Delaying electric circuit

Fig. 1. Experimental apparatus.

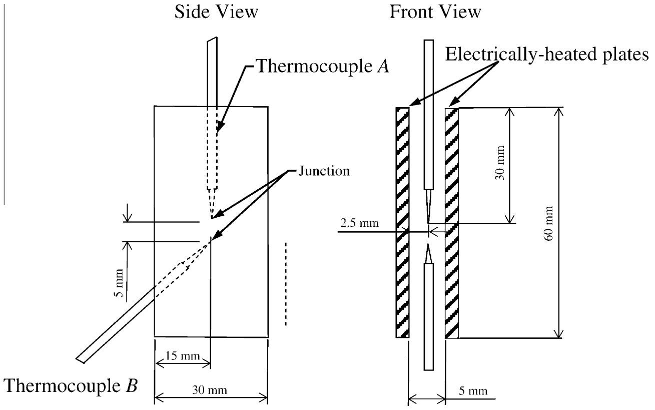


Fig. 2. Positions of thermocouples A and B.

temperature (monitored by thermocouple B) was achieved, the drop was conveyed into the hot environment by the linear motion mechanism. When the drop arrived at the right position (the center of the hot environment), the moving arm touched the optical switch (No. 11 in Fig. 1), which signaled the starting point of the heating process. A high-speed digital camera (No. 8 in Fig. 1) operated at 1000 frames per second recorded the heating and microexplosion behaviors of the emulsion drop. There was a delay circuit (No. 12 in Fig. 1) to set the delay time before the high speed camera was turned on. The delay was necessary because of the time limitation of the high speed camera, which could only record for just a few seconds. High speed camera was turned on before the flash lights to synchronize the time between the images with the data in the computer. The images were measured and then variations of the square of droplet diameter were plotted against time and can be used to compared with the d^2-law [21,22]. Note that for these droplets with irregular shapes, a meaningful determination of average droplet diameters is to measure the droplet area (A) in the images. Therefore, average droplet diameters (d) were obtained by analyzing the images taken by a high speed camera with image tool software (ImageJ). Average droplet diameter is defined as the hydraulic diameter $4A/p$, where p is the perimeter of droplet. Moreover, to monitor the heating history, the extensions of the thermocouples were connected to a data acquisition system (No. 7 in Fig. 1) with a rate of one temperature data point per millisecond.

The bio-oils were produced from pyrolysis of lauan (shorea) wood. The basic data of the bio-oil is shown in Table 1. Mixing ratio between pyrolysis bio-oil and fuel oil was one important parameter in this experiment. Before mixing the pyrolysis bio-oil and fuel oil, 0.2% surfactant and fuel oil were stirred for 1 min and then a certain amount of pyrolysis bio-oil was added according to the mixing ratio specified for 10 min at a fixed speed 9000 rpm using a stirring machine. The experiments were conducted at different ambient temperatures with a variety of volume-based mixing ratios (0% (pure fuel oil), 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100% of bio-oils). Two kinds of fuel oil were chosen, i.e., diesel and heavy fuel oil (HFO). Tables 2 and 3 show the properties of diesel and HFO, respectively. In bio-oil, the water content is 26.99%, and the oxygen content is 28.09%, which are much higher than those of diesel and HFO. The presence of high oxygen content is regarded as the biggest difference between bio-oil and fossil oil. Because of its high water and oxygen contents, the heating value of bio-oil, 4090 kcal/kg, is much lower than diesel and HFO (approximately about 40.10% of the heating value of diesel or 40.91% of the heating value of HFO). Bio-oil does not naturally blend with conventional fossil fuel. It may be possible to add a solvent or to emulsify mixtures of bio-oil and fuel oil in order to get homogeneous blends. The average initial diameter of the suspended drop was around 1 mm.

Table 1
Properties of the pyrolysis bio-oil of lauan wood.

Test item	Test results	Method
Water	26.99%	Karl-Fisher method
Ash	1.43%	CNS 3576
Flammable substance	71.58%	CNS 3577
Carbon	38.69%	NIEA R409.21C
Hydrogen	4.36%	NIEA R409.21C
Oxygen	28.09%	NIEA R409.21C
Nitrogen	0.24%	NIEA R409.21C
Sulfur	0.13%	NIEA R409.21C
Chlorine	0.07%	NIEA R409.21C
LHV	17.11 MJ/kg	NIEA R214.01C
HHV	18.79 MJ/kg	NIEA R214.01C

Fig. 3 shows some of the phenomena that may occur during the suspended drop experiment. In this experiment, the fuel used is fuel mixture of 40% bio-oil and 60% diesel. The ambient temperature is 500 °C and droplet diameter is 1.19 mm. Line A–B–C–D shows the temperature of the droplet. Line a–b–c–d–e indicates the diameter-squared of the drop. A–B is the period where the droplet absorbs heat from the surrounding. In period a–b the diameter of the droplet fluctuates a lot which indicates microexplosion occurred early in the experiment and then followed by evaporation in line b–c. c–d is the expansion phenomenon and finally it ends with the stable state condition shown in d–e where the droplet is at a stable size for a while. B–C period is the ignition event and the droplet burns in this time interval. After ignition occurs, the temperature becomes stable as shown in C–D. The results obtained were not all like Fig. 3. It depends on the parameters imposed on the experiment.

3. Results and discussion

Heating experiments for the droplets of diesel/bio-oil blends, HFO/bio-oil blends, pure diesel, pure HFO, and pure bio-oil were conducted at different ambient temperatures (T_∞) with a variety of mixing ratios under the atmospheric pressure.

3.1. Microexplosion and ignition of pure pyrolysis bio-oil

The evolution of the droplet diameter was plotted versus the heating time. Figs. 4 and 5 show the experimental results for pure

Table 2
Properties of diesel oil.

Test item	Test results	Method
Density (@15 °C)	0.8335 g/cm^3	ASTM D-287
Flash point	80 °C	ASTM D-93
Pour point	−9 °C	ASTM D-97
Viscosity (@40 °C)	3.024×10^{-6} m^2/s	ASTM D-445
Carbon residue	0.8 mg/g	ASTM D-524
Sulfur content	0.22 mg/g	ASTM D-129
Distillation TBP	202.4 °C	ASTM D-86
10%	229.4 °C	ASTM D-86
20%	241.6 °C	ASTM D-86
50%	270 °C	ASTM D-86
90%	334.2 °C	ASTM D-86
FBP	376.7 °C	ASTM D-86
Cetane index	53.2	ASTM D967-80
Mono-aromatic	247 mg/g	HPLC
>Di-aromatic	29 mg/g	HPLC
Hydrogen	124.6 mg/g	Element analyzer
Carbon	847.5 mg/g	Element analyzer
H/C ratio	1.815	Element analyzer
LHV	42.47 MJ/kg	ASTM D-240
HHV	45.92 MJ/kg	ASTM D-240

Table 3
Properties of heavy fuel oil.

Test item	Test results	Method
Density (@15.6 °C)	0.9533 g/cm^3	ASTM D-1298
Flow point	12 °C	ASTM D-97
Water	0.32 vol.%	ASTM D-95
Flash point	110 °C	ASTM D-93
Viscosity (@50 °C)	1.3×10^{-4} m^2/s	ASTM D-445
LHV	40.63 MJ/kg	ASTM D-240
HHV	42.93 MJ/kg	ASTM D-240
Carbon	88.11 wt.%	ASTM D-5291
Hydrogen	10.84 wt.%	ASTM D-5291
Nitrogen	2.763 mg/g	ASTM D-4629
Sulfur	0.46%	ASTM D-4622

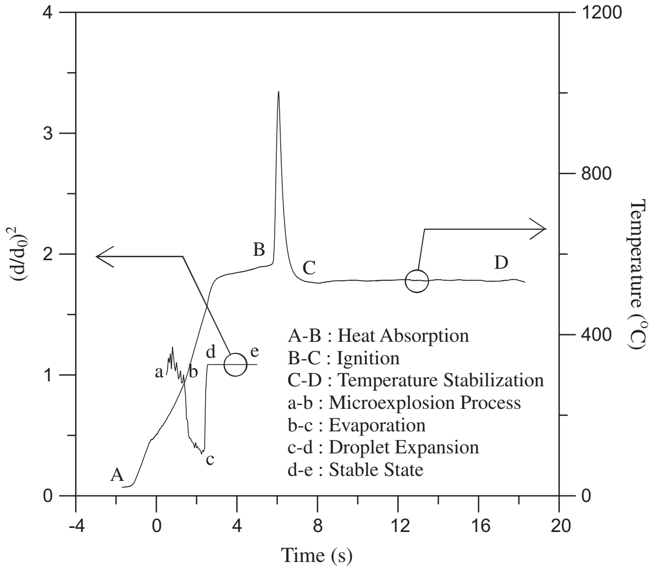


Fig. 3. Single droplet burning phenomenon.

bio-oil. In Fig. 4 at $T_\infty = 300$ °C, it can be seen that microexplosion and random behavior (expansion, bubbling, ejection and swelling) occurred during the experiment. These behaviors are shown by the violent fluctuation of the squared-diameter of the droplet from $t = 0–5$ s, which can also be seen in the images sequence at $t = 0.263$, 1.472, and 1.731 s. Random behavior is the condition where the size of the droplet kept changing unpredictably. Random behavior and microexplosion occurred because of bubbling. The bubbling phase is characterized by the formation of small bubbles that move toward the surface of the droplet where they explode to produce small fragments (see the image at $t = 1.47$ s). The bio-oil tested was a multi-component fuel which contains many types of compounds with various boiling points and high water content (26.99%). High percentage of water contents inside the bio-oils also become the major factors for the occurrence of bubbling and microexplosion. Law [23] explained the basic mechanism responsible for microexplosion based on the diffusion-limit model. The droplet surface becomes more concentrated with the less volatile, high-boiling-point component, and the droplet interior has a higher concentration of the more volatile, low-boiling-point component. Thus it is possible that the liquid elements in the droplet interior can be heated beyond its local boiling point and then possess substantial amount of superheat. Consequently, the liquid element will homogenously nucleate and gasify, leading to intense internal pressure build-up and thereby the catastrophic fragmentation of the droplet. This mechanism can be used to explain the microexplosion phenomena observed in this study. Droplet diameter changes cannot be predicted when the microexplosion and random behaviors occurs. Ignition was not found in all cases for $T_\infty = 300$ °C. Ignition is expected to be initiated in a narrow region next to the hot ambience, which has the highest temperature [23]. There are two reasons why ignition did not occur for pure bio-oil droplet: (1) The ambient temperature was not high enough to ignite the droplet. (2) Besides the ambient temperature, the key parameter to determine ignitability of a fuel is the boiling point or the range of boiling point of the fuel. When the boiling point of a fuel is relatively too high at specified ambient temperature, the fuel vapor concentration near the droplet surface is not high enough to reach the lower flammability limit of the fuel so that the ignition does not occur.

At higher temperatures, e.g. $T_\infty = 500$ °C in Fig. 5, microexplosion and random behaviors occurred from $t = 0–2$ s followed by expansion, as can be seen in the image at $t = 3.648$ s. After the occurrence of expansion, the droplets size nearly stayed the same because of the heterogeneous combustion of cenospheres, i.e., the carbonaceous particle formed by pyrolysis oils during the last stages of droplet combustion [20]. Ignition and then droplet burning can be observed in this case, as shown by the changing of temperature curve during the period from $t = 3.8–5$ s. Droplet burning can also be seen in the image at $t = 3.821$ s where the flame had appeared.

3.2. Microexplosion and ignition of the drops of pyrolysis bio-oil/diesel blends

Experiments using emulsion drops of fast pyrolysis bio-oil/diesel blends was conducted for 5% bio-oil and each multiple of ten percent in the mixture. The experimental results show that with more bio-oil content in the blends, more unstable the emulsion becomes, as already explained above that the bio-oil itself basically consists of many components. Therefore, adding just a little bio-oil in the diesel can result in microexplosion and random behavior (expansion, bubbling, ejection and swelling). More bio-oil significantly led to the phenomenon that microexplosion and random behavior occurred more frequently and more quickly.

Microexplosion and random behavior occurred for all cases of bio-oil/diesel emulsions. However, at low percentages of bio-oil in the diesel oil, diesel dominated the fuel properties so that random behavior and microexplosion were not violent, as shown in Fig. 6. Expansion occurred at $t = 0.33$ s where the droplets size changed a little bit, as shown by the image at $t = 0.33$ s in Fig. 6. Not many carbonaceous particles could be formed due to the small amount of bio-oil so that the drop expansion could barely be observed. Accordingly, a tiny amount of fuel left on the thermocouple and finally ignition occurred, as shown by the dramatic temperature increase at the time interval from $t = 1.4–2$ s and the flame appearance in the image at $t = 1.4$ s.

Increasing the amount of bio-oil will increase the emergence of microexplosion and random behavior as shown by the squared-diameter of droplet and image sequence at $t = 1.296$ s in Fig. 7. Expansion can be observed in this case as shown in image sequence at $t = 4.212$ s followed by ignition at $t = 4.462$ s. A lot of carbonaceous particles formed when the amount of bio-oil increased so that the expansion could be observed more clearly.

3.3. Ignition of the emulsion drop of pyrolysis bio-oil/HFO blends

Suspended droplet experiments were also conducted for the cases of bio-oil/HFO blends. Random behavior (bubbling, expansion, ejecting, and swelling) and microexplosion could mostly be found in these cases. However, ignition only occurred in a few cases for the bio-oil/HFO blends with a higher bio-oil content.

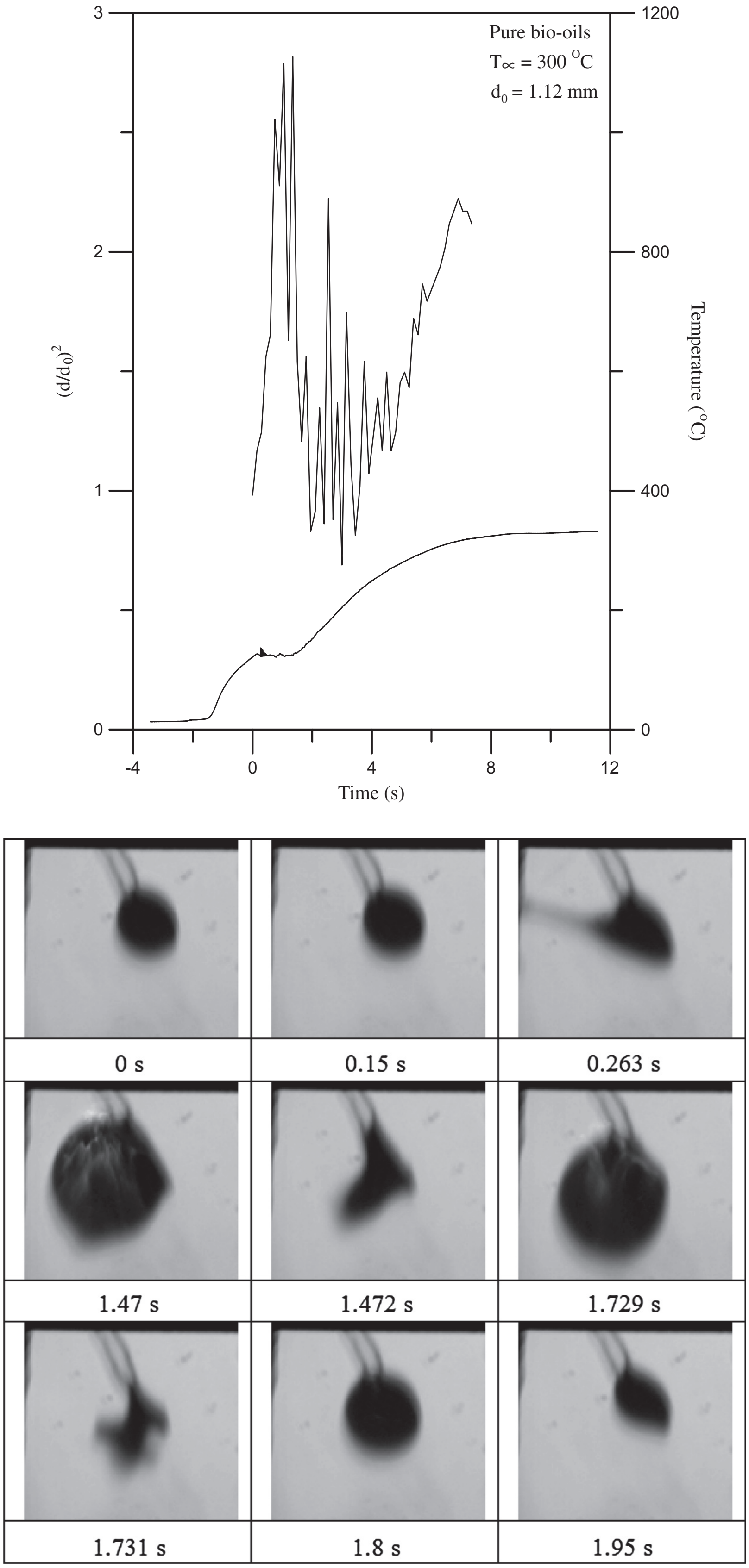
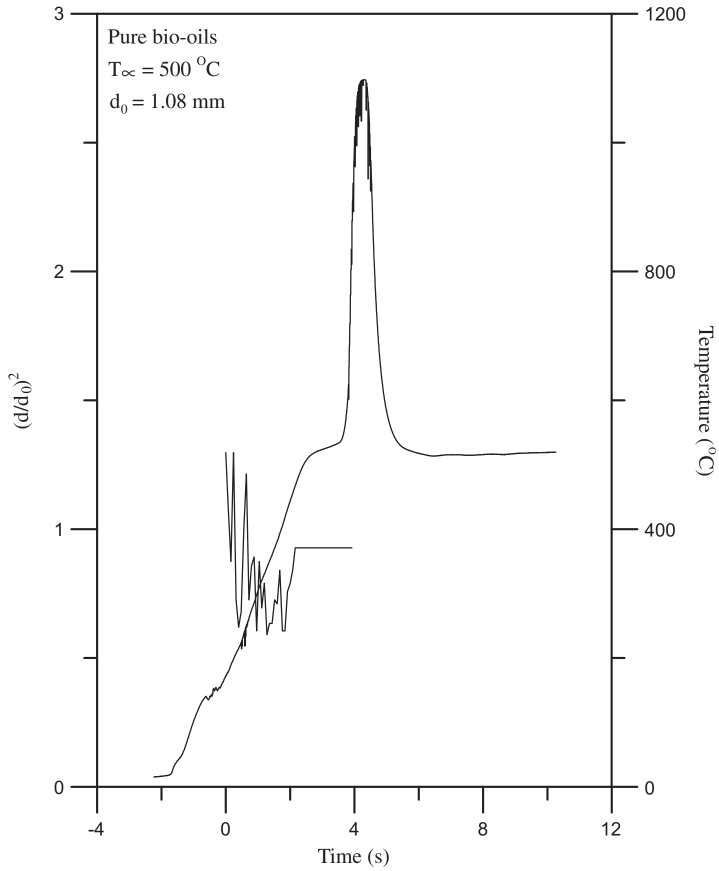


Fig. 4. Pure bio-oils at 300 °C.

For bio-oil/HFO blends, evaporation and bubbling occurred very slowly but their microexplosion intensity was stronger than bio-oil/diesel blends. At a low bio-oil content (5%) in bio-oil/HFO blends, stronger microexplosion occurred (Fig. 8) compared with bio-oil/diesel blends with 5% bio-oil (Fig. 6) in which the occurrence of microexplosion was weaker but faster. The droplets size



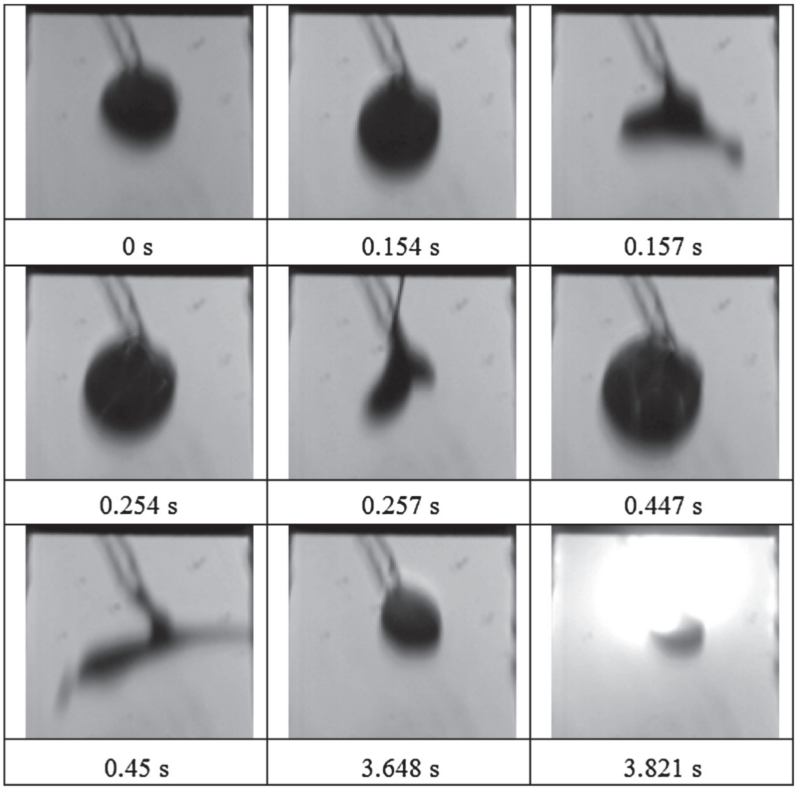


Fig. 5. Pure bio-oils at 500 °C.

increased up to 2 times of the initial size before exploding, as shown in squared-diameter curves at $t = 2$ s. The reason was that HFO itself has higher boiling point than diesel, so that in the bio-oil/HFO blends, the occurrence of evaporation and bubbling was slower than in bio-oil/diesel blends. Additionally, the viscosity of HFO is higher than diesel, thus bigger bubble is needed for

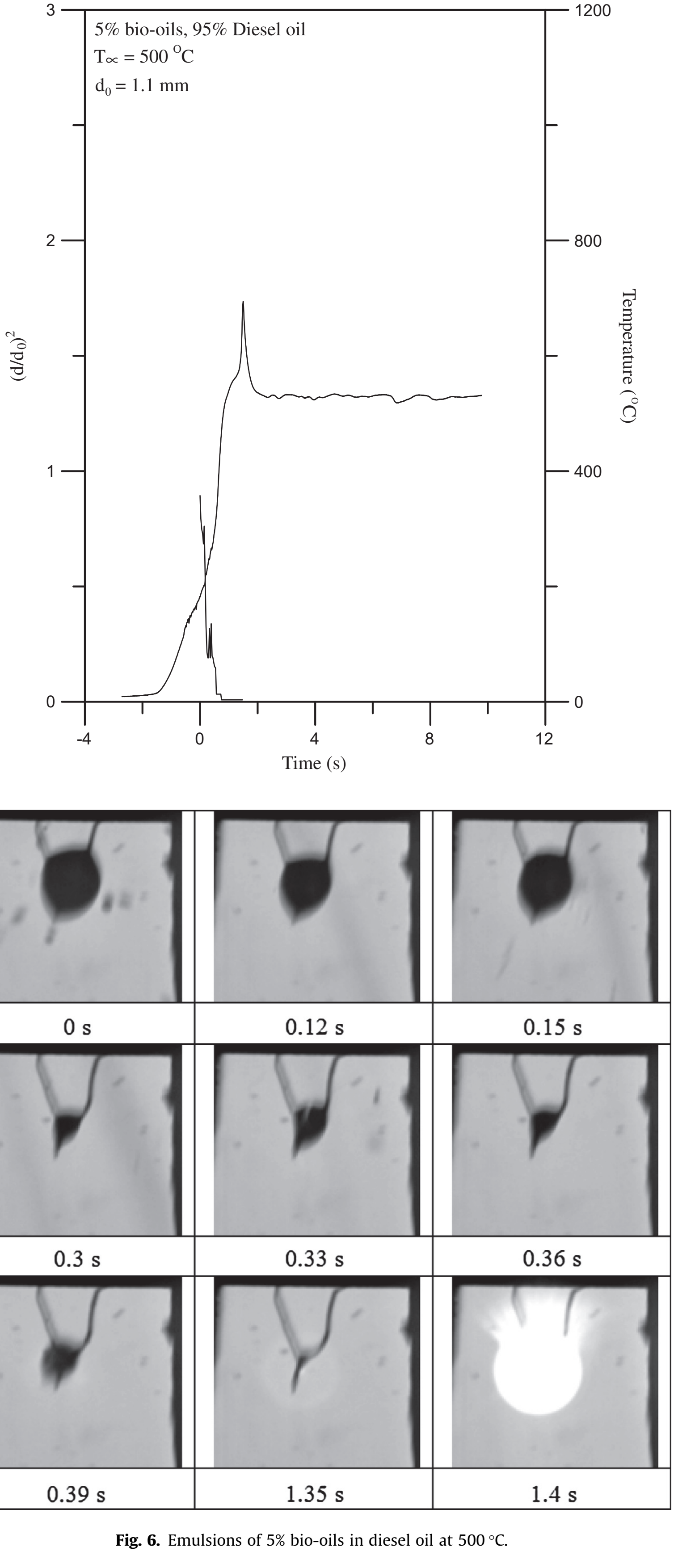


Fig. 6. Emulsions of 5% bio-oils in diesel oil at 500 °C.

explosion. For a small amount of bio-oil in the bio-oil/HFO blends, ignition could not be observed. The environment temperature 500 °C is not high enough to ignite the droplets. However, at higher percentage of bio-oil at 500 °C, ignition occurred. Ignition started

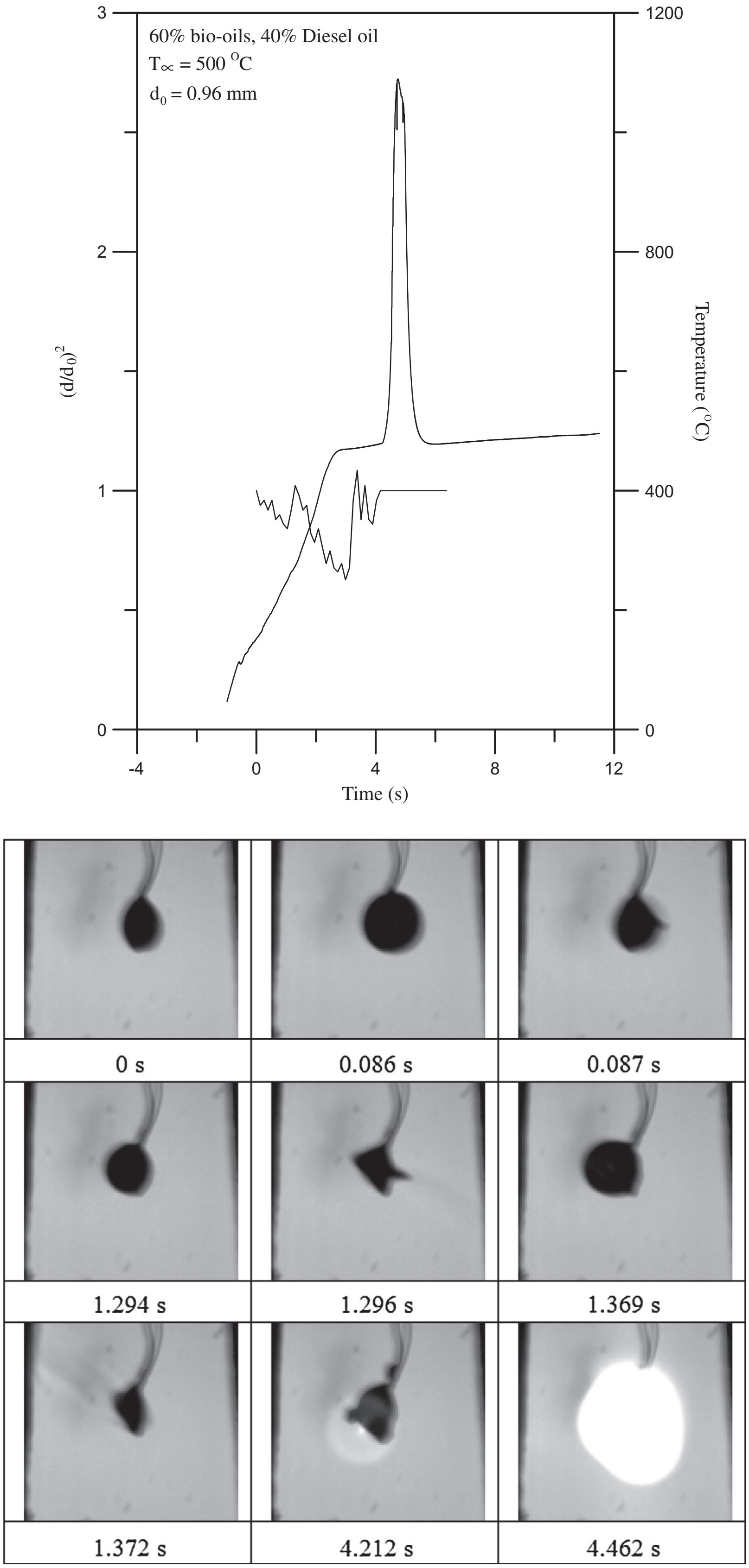


Fig. 7. Emulsions of 60% bio-oils in diesel oil at 500 °C.

from the case with 60% bio-oil content in the bio-oil/HFO blends. Fig. 9 depicts that with 70% bio-oil content in the bio-oil/HFO blends at $T_\infty = 500\ ^\circ\mathrm{C}$, ignition occurred during the period from $t = 9–11$ s as shown by the sharp increase in the temperature curve.

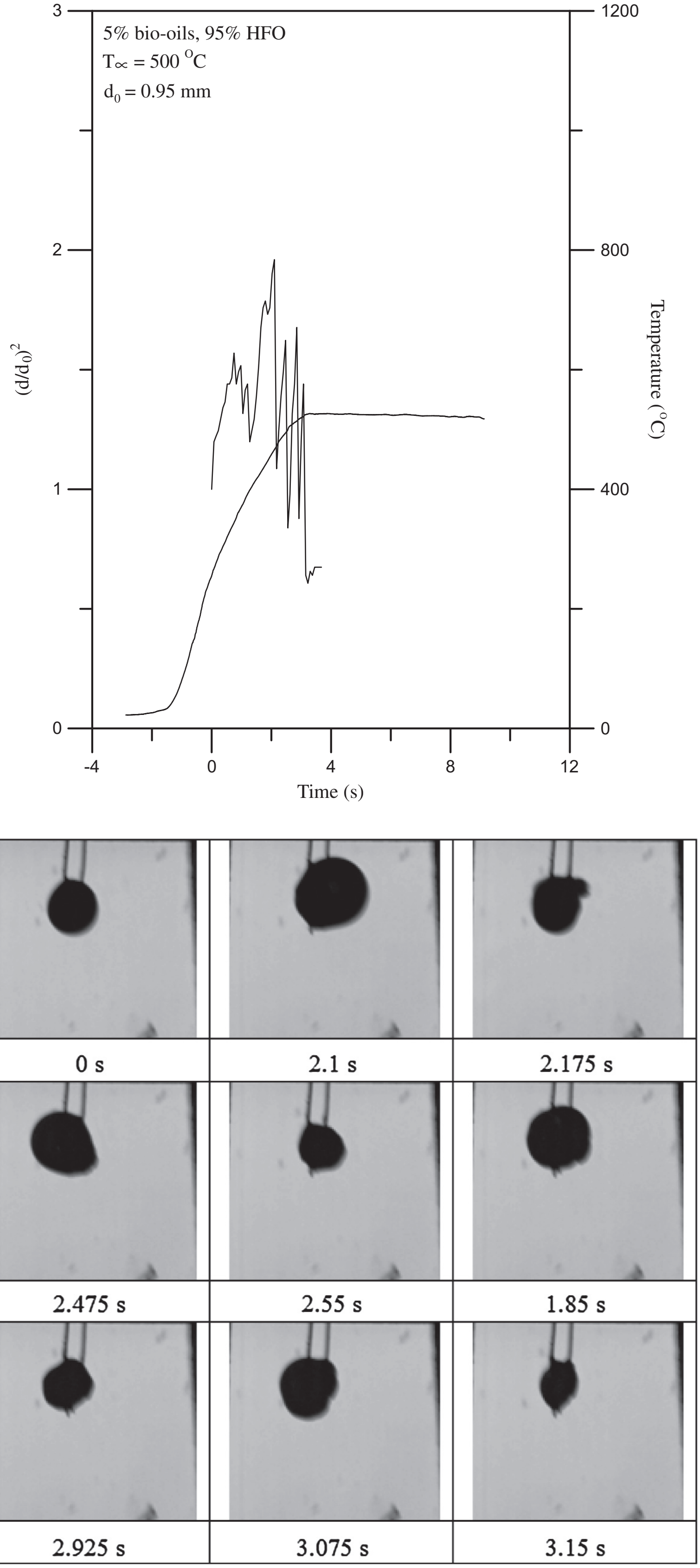


Fig. 8. Emulsions of 5% bio-oils in heavy oil at 500 °C.

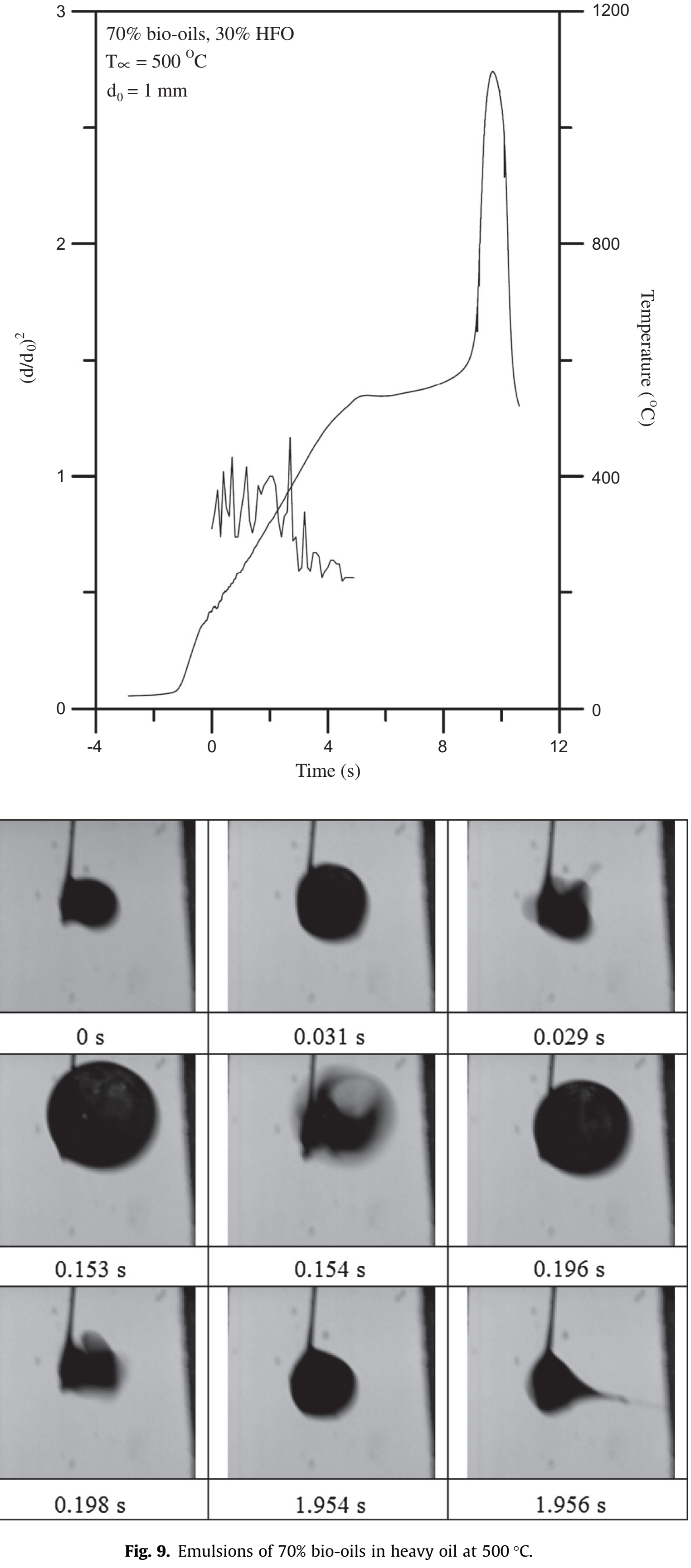


Fig. 9. Emulsions of 70% bio-oils in heavy oil at 500 °C.

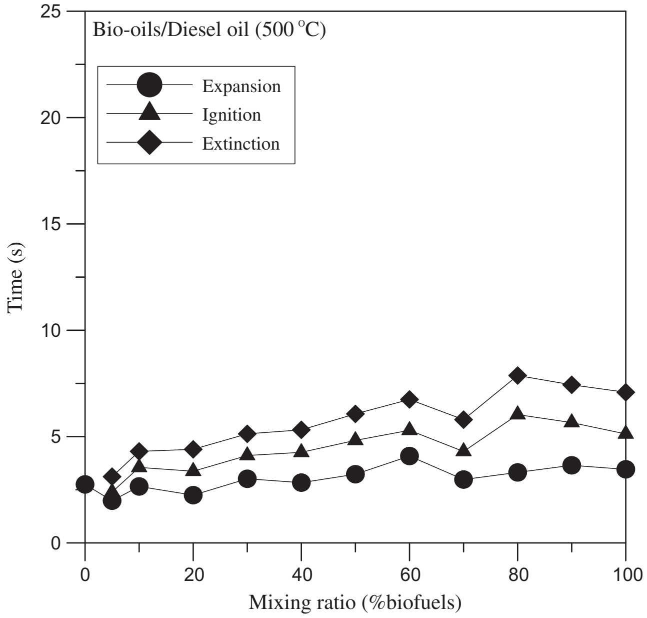


Fig. 10. Burning cases of emulsions of bio-oils/diesel oil.

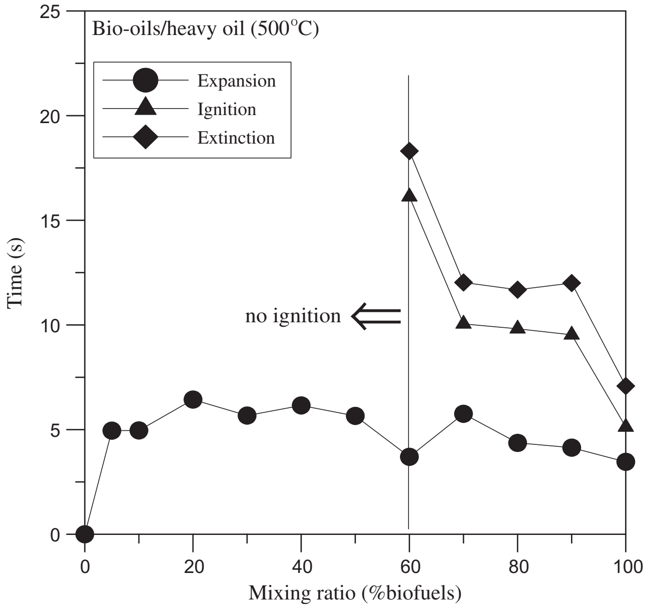


Fig. 11. Burning cases of emulsions of bio-oils/heavy oil.

3.4. Droplet ignition of the bio-oil/diesel blends and bio-oil/HFO blends

For the droplet ignition of the bio-oil/diesel blends and bio-oil/HFO blends, there were three stages observed. All the cases had a similar profile of temperature curve with heat absorption at the beginning followed by a drastic increase of temperature (ignition) and finally the temperature stabilization.

In the ignition cases, time interval of each stage became the major difference. Figs. 10 and 11 show the time interval for each stage and three time intervals were recorded, i.e., expansion, ignition and extinction. In the expansion state, evaporation and bubbling phase occurred. Ignition means the onset of burning. And the last is extinction when the burning was finished and the droplet completely burned or the char-like material after combustion was left on the thermocouple junction.

For bio-oil/diesel blends (see Fig. 10), the results show that as there was more bio-oil in the blends, every stage became longer, not only for evaporation and bubbling but also for the expansion and ignition interval. More bio-oil means more carbonaceous particle formed so the expansion became longer. Furthermore, more bio-oil made the droplet became more unstable so that the microexplosion and random behavior (bubbling state) became longer. And also the burning became longer because more bio-oil means more flammable substance inside and slower burning speed. The heating value of bio-oil is low compared with diesel, and the water content also increases by increasing the amount of bio-oil.

For bio-oil/HFO blends (see Fig. 11), ignition did not occur for the cases with 0–50% bio-oil inside the blends. However, when we added more bio-oil inside the blends (equal to or greater than 60% bio-oil), ignition could occur. It was difficult to burn HFO even at 500 °C. At 500 °C, the occurrences of ignition and extinction of bio-oil/HFO blends (Fig. 11) were slower compared with those of bio-oil/diesel blends (Fig. 10). At a higher percentage (more than 50%), ignition was found but the ignition time is long. The ignition time decreased with an increase of bio-oil as shown in Fig. 11. The key point for bio-oil/HFO blends at 500 °C is that a greater bio-oil content corresponding to a larger amount of flammable substance so that the ignition became faster.

4. Conclusions

Heating experiments for the suspended droplets of the bio-oil/diesel blends and bio-oil/HFO blends were conducted to observe the vaporization, microexplosion and ignition phenomena. Mixing ratios of blended fuels and temperatures of the hot environment are two important parameters investigated herein. Concluding remarks are addressed as follows.

For the droplet of pure bio-oil at low ambient temperature of 300 °C, the phenomena of expansion, bubbling, ejection and swelling were found, but ignition did not occur. At a higher hot environment temperature of 500 °C, microexplosion, random behavior (expansion, bubbling, ejection and swelling), ignition and extinction occurred.

For the bio-oil/diesel blends, at low percentages of bio-oil, diesel dominated the fuel properties so that microexplosion and ignition could not be found easily. For higher bio-oil contents in the bio-oil/diesel blends at the environment temperature of 500 °C, micro-explosion occurred more frequently, and expansion followed by ignition could be observed more clearly. Some of the particles contained in the bio-oil expanded at the end of the droplet lifetime and the char-like droplet maintained its size for several seconds before finally burned. In the case of 500 °C, ignition occurred after expansion followed by a stable state, which only took a short period of time.

For the bio-oil/HFO blends, ignition did not occur for the lower bio-oil contents (smaller than 50%) in the blends. However, when the bio-oil content was equal to or greater than 60%, ignition could occur but it took longer time for bio-oil/HFO blends to burn out compared with the bio-oil/diesel blends.

In order to understand the significant differences between the present lab experiment and feasible practical application, it would be necessary to address the impact of pressure and temperature on the results obtained using the current technique. For example, if bio-oils are to be used in diesel engines, the pressure would be much higher. If used in boilers, the ambient temperature would be much higher than that studied here. It was reported that other factors, such as the ambient temperature and pressure, have no direct effect on microexplosion strength [24]. However, raising the temperature will speed up the onset of microexplosion [24], and increasing the pressure will enhance the possibility of microexplosion [24,25]. The reasons are addressed as follows. When temperature is relatively high, the heat flux is large. Therefore, it is expected that a higher temperature would result in a higher rate of heat transfer; which in turn accelerates the occurrence of microexplosion. Similar to temperature, pressure poses no direct effect on a microexplosion. However, higher pressure increases the boiling point of heavy component, and this enhances the possibility of microexplosion [24,25]. In addition, the solubility of gas will increase under higher pressure, leading to a quicker onset of a microexplosion [24]. It is inferred that increasing temperature or decreasing pressure may also cause the decrease of the ignition delay time and droplet lifetime.

Regarding the experimental results in this study, we realize that the understanding on the effects of ambient temperature and pressure on droplet vaporization and ignition for pyrolysis-derived bio-oil and its mixtures with a conventional diesel fuel and a heavy fuel oil should be verified and further explored by the experiments. Considering the main practical applications of pyrolysis-derived bio-oil used in boilers and industrial furnaces, two experimental facilities [26,27] are suitable for further investigating. In our recent study [26], the experimental setup consisted of a drop generation system and a combustion system which will be used to investigate the characteristics of drop strings of different spacing in a high-temperature oxidizing environment. In addition, a 300 kWth multi-fuel combustion test furnace [27] can be employed to examine the operational characteristics using bio-oil as fuel. Detailed comparisons between this work and the experimental investigations done by the above facilities will be addressed in separate studies in the near future.

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